Computational Design of Parameters of IRT-2M Fuel with Enrichment below 20% for Low Power Research Reactors

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ABSTRACT

This article focuses briefly on characteristics of a possible procedure during reduction of fuel enrichment of two research reactors in the Czech Republic, i.e., LVR-15 research reactor (power up to 15 MW) at NRI Rez and VR-1 training reactor (power up to 5 kW) at CTU Prague. Both reactors are now operating with fuel enriched to 36% of ^{235}U. While the LVR-15 reactor uses Russian IRT-2M fuel, the VR-1 reactor has been operating on IRT-3M fuel for five years already. The goal for both reactors until now was to use Russian IRT-4M fuel with ^{235}U enrichment below 20%. The original idea that the LVR-15 reactor would go through the IRT-3M fuel during the transition to IRT-4M fuel now seems baseless. The article hence shows a possible solution to the current situation for the VR-1 reactor. A convenient solution (based on consultations with the Russian producer) could be a preparation of fuel of IRT-2M geometry with enrichment to 20% of ^{235}U. Such a fuel would not be intended for power research reactors in the first step but for reactors with power up to 100 – 200 kW. The article presents a proposal of this fuel (said proposal was created on the basis of many years' standing experience of operation at VR-1 reactor) and verifying calculations for selected configurations. As for enrichment, matrix, and content of uranium the proposal is based on verified capability of the Russian producer. Emphasis is placed on the necessity of the fuel having a long lifetime in the light water reactors.

1. Introduction

The status of the RERTR program in the Czech Republic in summer 2002 can be characterized as follows: Both reactors (the research reactor LVR-15 in the Nuclear Research Institute in Rez and the training reactor VR-1 Sparrow in the Czech Technical University in Prague) are operated with fuel assemblies of known Russian type IRT, enrichment 36%. The reactor LVR-15 uses the IRT-2M type of fuel and the reactor VR-1 uses IRT-3M assemblies. This means that the current status remains the same as in the last 3 years. The program was originally expected to continue over the next several years in four main steps:

- The changes of type IRT-2M to IRT-3M (enrichment 36%) in the research reactor LVR-15 (at first to mixed core IRT-2M and IRT-3M, later to core IRT-3M only).
- The changes from the type IRT-3M to IRT-4M (enrichment below 20%) on the training reactor VR-1. The type IRT-4M (Russian production) is not prepared yet. The fuel assemblies IRT-3M from the reactor VR-1 will be used in the reactor LVR-15.
- The changes from type IRT-3M into IRT-4M (enrichment below 20%) in the research reactor LVR-15 (at first to mixed core IRT-3M and IRT-4M, later to core IRT-4M only).
- The end of the RERTR program in the Czech Republic.

Now it is becoming clear that certain significant changes will have to be made in the program, implied by the fact that the LVR-15 research reactor will not (even for the originally planned temporary period) use the IRT-3M type of fuel with 36% enrichment, i.e., the type that has been used in the VR-1 reactor and was purchased in 1997 within the Czech program of reduced-enrichment fuel for VR-1 (from 1990 until early 1997, this reactor worked with IRT-2M type of fuel with 36% enrichment). Current operational experience and recommendations indicate that, even if all requirements and recommendations for cleanness of moderator – including water circulation through the active core (the VR-1 reactor has no forced cooling, the generated power is removed by natural convention only) – are strictly adhered to, this type of fuel is not suitable for long-term (i.e., for longer than about 6 years) use. Since the fuel cannot thus be used in the LVR-15 reactor, a substitute solution has to be sought. This is realistic in cooperation with the producer of the fuel, which is Novosibirsk Chemical Concentrates Plant, Inc.

2. General Setting for Model Calculations of New Fuel

On the basis of consultations with the fuel manufacturer, a setting for draft calculations was prepared with IRT-2M geometrical setup and with 19.75% ^{235}U enrichment. Another assumption is that the fuel matrix will be UO_2 (dispersed in Al) and weight (partial) representation of uranium between 3.0 and 3.2 g U/cm^3. It is important that the (aluminium) cover of the fuel should be sufficiently thick to guarantee long-term (more than ten years') use of the fuel in light-water basin reactors. The fuel is not designed for high-power research reactors but for reactors with heat power at 100 kW and working time up to 2,500 hours per year. Hence it is not necessary to create in the fuel a spare quantity of fissile ^{235}U, which would enable a high degree of fuel burn-up, as is usual for high-power research reactors. Neutron parameters will be compared with those of the standard IRT-2M type of fuel with 36% enrichment ^{235}U, for selected configurations of the active core typical of research and school reactors with power output up to 100 kW. The already-mentioned operational experience with the IRT-2M type of fuel with 36% enrichment, which has been used in the VR-1 reactor for several years now, makes such comparison viable.

3. Model Calculations

3.1. Calculation methodology

For neutron calculations of the new (model) IRT-2M type of fuel with 19.75% enrichment for the VR-1 reactor, the established method of calculation is used, with the aid of the MCNP 4C software and the ENDF/B-6 nuclear data library. The tested and used MNCP input file for the existing IRT-3M type of fuel with 36% enrichment was used as the input file for the new fuel as well. The active core grid model, all absorption rods, channels and most of the previously used components have been maintained in the input file.

In the first step, fuel geometry adjustments from IRT-3M to IRT-2M took place, while preserving the square shape of the fuel. The aluminium cover thickness was changed to 0.55 mm, thickness of the uranium core to 0.9 mm and height of the uranium core to 59 cm. Density and isotope composition of the core and cover were also adjusted.

In the second step, roundness of IRT-2M corners was modelled. The fuel pipe consists of four straight and four rounded parts; a rounded part is defined as $^1/_4$ of cylinder cladding with an outside diameter of 0.65 cm and an inside diameter of 0.45 cm. A section of the rounded part

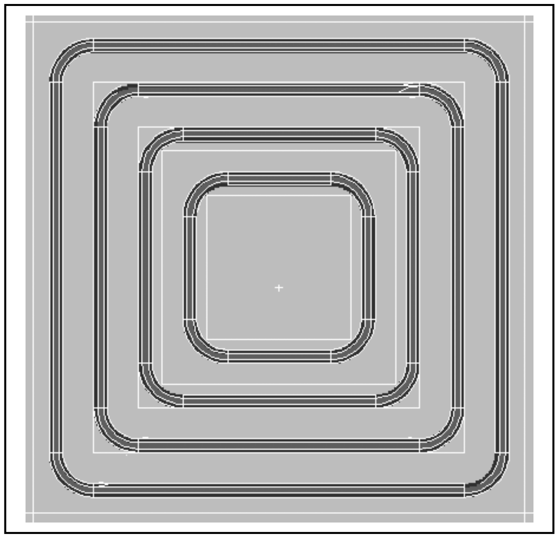

Fig. 1. IRT-2M Fuel assembly model in MCNP code

model is shown in Fig. 1. The displacement medium used for forced cooling of the fuel was not modelled.

For the above-defined fuel, dependence of the multiplication factor on uranium density, moderator density and fuel meat thickness was calculated – these calculations took place in a hypothetical (modelled) active core with 20 fuel elements (4×5 elements, out of which 14 are four-pipe ones and 6 are three-pipe ones, with the IRT-2M geometrical setup, 0.55 mm cover thickness, 19.75% enrichment, 7 regulation rods with a Cd absorber; there are five channels with 56 mm-φ at the active core) – cf. Fig. 2.

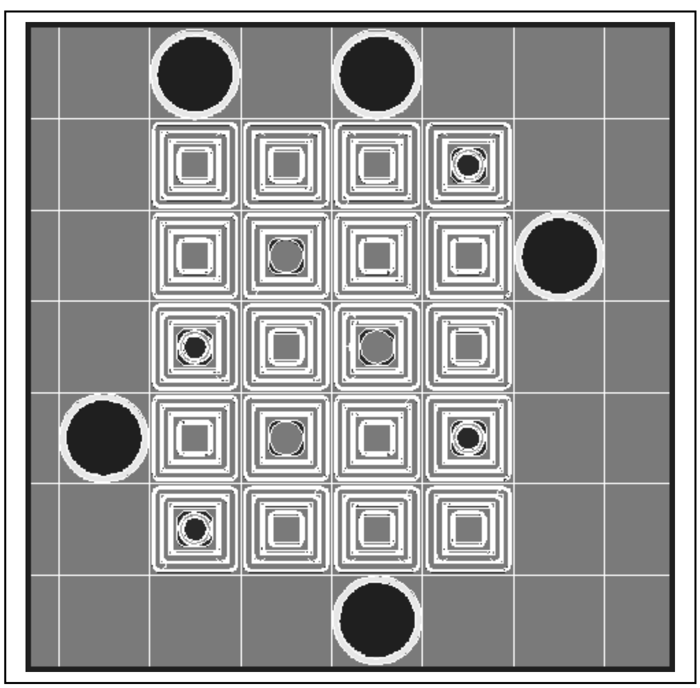

Fig. 2. Hypotetical Core configuration with 20 fuel assemblies

Comparison and testing calculations were then carried out with A1 and A2 active cores, which were operated in the VR-1 reactor in the period 1991-1992 with the IRT-2M type of fuel with 36% enrichment. A preliminary proposal of VR-1 operational active core was made in conclusion.

3.2. Dependence of the multiplication factor on uranium density

Uranium density values were tested in the range from 2.1 to 3.6 g/cm^3, with water density 1.0 and fuel meat length at 580 mm. The results, shown in Fig. 3, have the shape envisaged by the physical theory: the effective multiplication factor lies between 0.995 and 1.085.

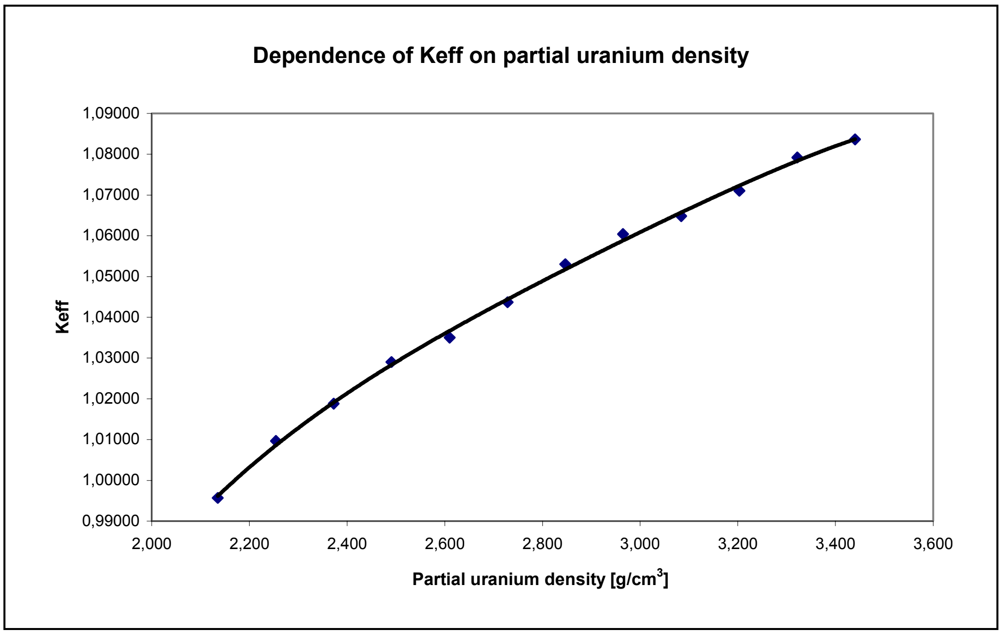

Fig. 3. Dependence of K_{eff} on partial uranium density

3.3. Dependence of the multiplication factor on moderator density

The moderator density values were tested in the range from 0.97 to 1.02. The results are shown in Fig. 4 and also correspond to theoretical ones. The preset partial density of uranium was 3.186 g/cm^3 and fuel meat length was 580 mm.

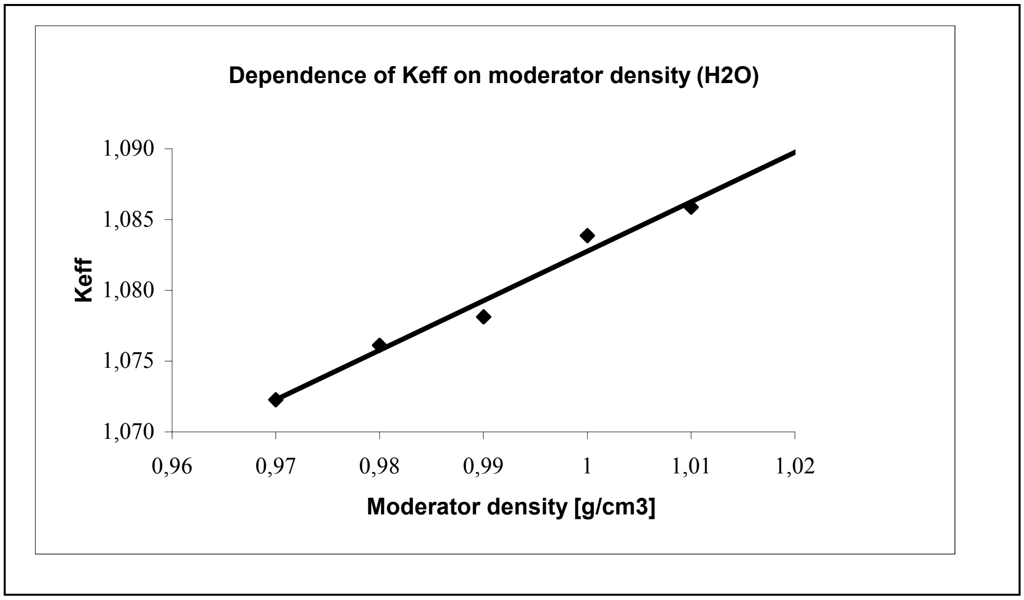

Fig. 4. Dependence of K_{eff} on moderator density (H_2O)

3.4. Dependence of the multiplication factor on fuel meat length in fuel element

The fuel meat length values were tested in the range from 570 mm to 600 mm, with water density 1.00 partial density of uranium 3.009 g/cm^3. The results are shown in Fig. 5.

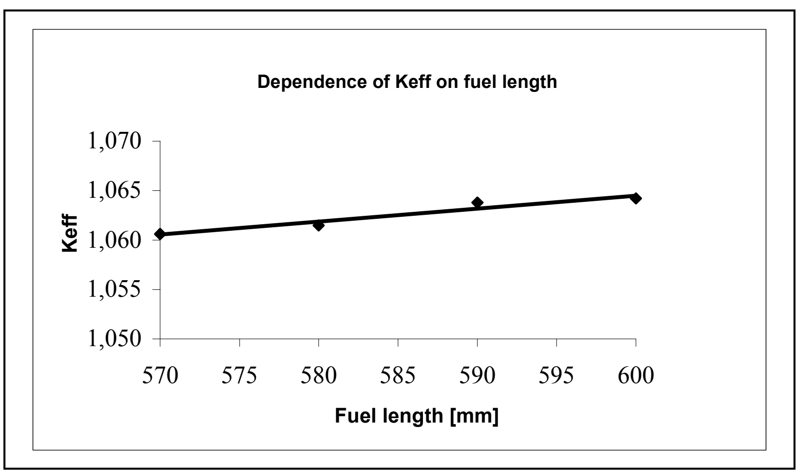

Fig. 5. Dependence of K_{eff} on fuel length

On the basis of the calculations, 4 preliminary proposals of IRT-2M geometrical setup were created, with 19.75% ^{235}U enrichment, with the parameters shown in Tab. 1. For the sake of completeness, the Tab. 1 also states similar parameters of IRT-2M with 36% enrichment.

4. Comparison Calculations

The comparison calculations' goal was to verify the calculations as such (by comparison with exactly defined experimental values) and also to compare selected configurations of the "original" and (several) new types of the IRT-2M type of fuel.

4.1. Verification calculations with operationally verified A1 and A2 active core

After creation of several models for the IRT-2M type of fuel with 19.75% and 36% enrichment, comparison calculations were carried out for A1 and A2 active cores, which were operated in the VR-1 reactor in the years 1991-1992 with the IRT-2M fuel and 36% enrichment. For each configuration of the active core, one exactly measured critical status was chosen, and this status was verified by calculations. The operational A1 and A2 active cores of the VR-1 reactor are shown in Fig. 6 and 7.

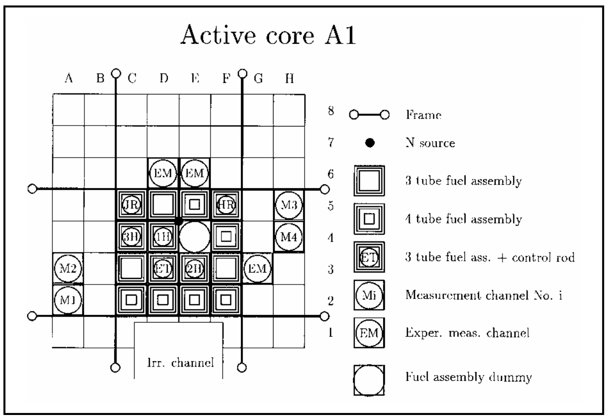

Fig. 6. Operational Core configuration A1

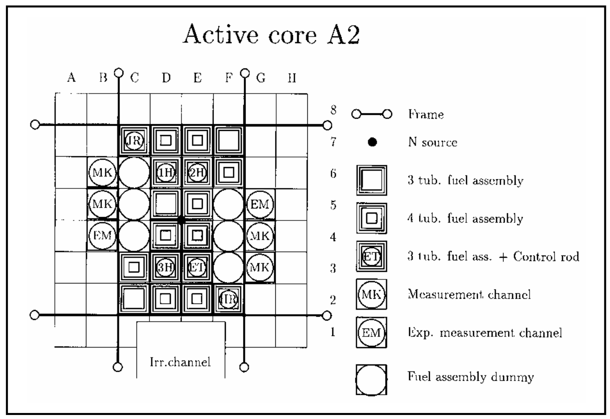

Fig. 7. Operational Core configuration A2

For the A1 active core, the chosen critical status was the one at which the H1, H2 and H3 safety rods are in the uppermost positions (680 mm); for the remaining rods E1 = 420 mm, JR = 350 mm, HR = 451 mm, and E2 is outside of the active core. The resulting multiplication factor is $k_{ef} = 0.99175 \pm 0.00096$ ($\rho = -1.07 \pm 0.12\ \beta_{ef}$). The calculation model is not, at this moment, able to calculate influence of 56mm-φ channels with RJ 1300 measurement chambers; hence this influence was not considered in the calculation. The influence of the channels at positions D6, E6 and G3 was experimentally determined as $-0.83\ \beta_{ef}$. After subtraction of that, the calculated reactivity value results in $\rho = -0.24 \pm 0.12\ \beta_{ef}$. The calculation can also be affected by the fact that each fuel element contains a different quantity of ^{235}U; the model calculation is based on elements with average quantity according to the catalogue. For the A1 core, there was 3131.9 g of ^{235}U in the reactor, while the calculation was based on a quantity of 3174.6 g of ^{235}U.

For the A2 active core the chosen critical status was the one at which the H1, H2 and H3 safety rods are in the uppermost positions (680 mm); for the remaining rods E1 = 000 mm (bottom position), JR = 411 mm, HR = 359 mm, and E2 is outside of the active core. The resulting multiplication factor is l $k_{ef} = 0.99284 \pm 0.00096$ ($\rho = -0.92 \pm 0.13\ \beta_{ef}$). Similarly to the A1 core calculation, influence of 56mm–φ channels with RJ 1300 measurement chambers is not taken into account. After subtraction of that, the calculated reactivity value results in $\rho = +0.33 \pm 0.13\ \beta_{ef}$. There was 3823.8 g of ^{235}U in the reactor, while the calculation was based on a quantity of 3834.8 g of ^{235}U.

On the basis of the calculation results, the accuracy of the calculations was assessed as satisfactory and both configurations were re-calculated with all four proposed types of IRT-2M fuel geometrical setup and with uranium enrichment at 19.75% (cf. Tab. 1). The results are shown in Tab. 2.

Tab. 1. Proposed types of IRT-2M fuel

	Fuel type 1	Fuel type 2	Fuel type 3	Fuel type 4	Fuel type 5 (original fuel)
Cladding [mm]	0,55	0,55	0,55	0,6	0,55
Enrichment [%]	19,75	19,75	19,75	19,75	36,00
Meat density [g/cm^3]	5,237	5,385	5,304	5,392	4,174
Partial uranium density [g/cm^3]	3,009	3,186	3,089	3,194	1,748
Amount of the ^{235}U in 3-tube fuel [g]	188,0	199,0	193,0	177,0	199,0
Amount of the ^{235}U in 4-tube fuel [g]	217,8	230,6	223,6	205,0	230,6

Tab. 2. Verification calculations for proposed types of IRT-2M fuel

	Fuel type 1	Fuel type 2	Fuel type 3	Fuel type 4	Fuel type 5 (original fuel)
Core configuration A1	k_{eff} = 0,98035 ± 0,00094 ρ = -2,57[βef]	k_{eff} = 0,99175 ± 0,00096 ρ = -1,07[βef]	k_{eff} = 0,99175 ± 0,00089 ρ = -1,88[βef]	k_{eff} = 0,97098 ± 0,00085 ρ = -3,83[βef]	k_{eff} = 1,0000 ρ = 0,00[βef] (experiment)
Core configuration A2	k_{eff} = 0,98130 ± 0,00096 ρ = -2,44[βef]	k_{eff} = 0,99284 ± 0,00096 ρ = -0,92[βef]	k_{eff} = 0,98827 ± 0,00086 ρ = -1,52[βef]	k_{eff} = 0,97198 ± 0,00098 ρ = -3,70[βef]	k_{eff} = 1,0000 ρ = 0,00[βef] (experiment)

4.2. Calculation proposal of an active core with IRT-2M fuel and 19.75% enrichment

The calculations of operationally verified A1 and A2 active cores with the new types of fuel (Tab. 1 and 2) provided sub-critical statuses (as had been expected); hence a new configuration of the active core was proposed for a new series of calculations. The configuration consists of 10 four-pipe and 6 three-pipe IRT-2M elements with 19.75% enrichment. This configuration is shown in Fig. 8. The calculation is made for the status on which the H1, H2, H3 and E1 rods are in the uppermost positions; for the remaining rods JR = 340 mm, HR = 340 mm, and E2 is outside of the active core.

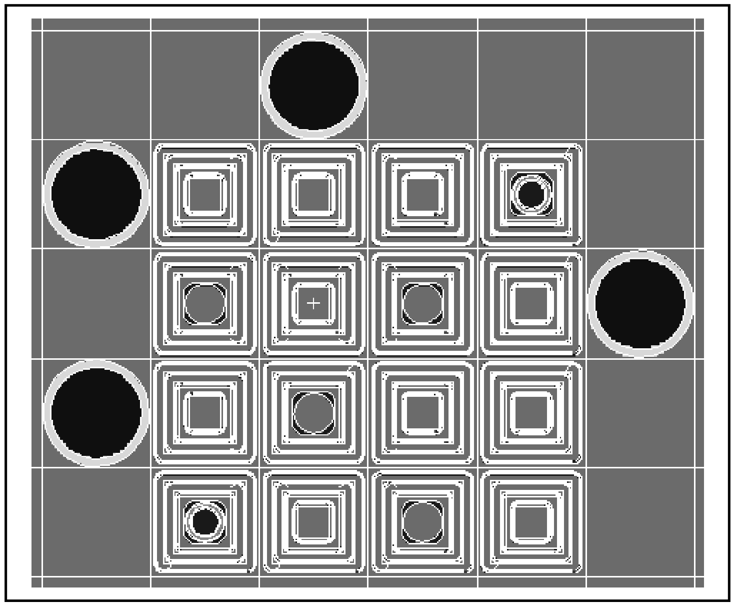

Fig. 8. Preliminary Core configuration with new fuel assemblies

Results of the calculations are shown in Tab. 3. Similarly to calculations made for A1 and A2 active cores, influence of 56mm–φ channels with RJ 1300 measurement chambers is not taken into account; this influence is estimated as approx. between 0.90 and 1.00 β_{ef}.

Tab. 3. Results of the calculations for proposed types of IRT-2M fuel

	Fuel type 1	Fuel type 2	Fuel type 3	Fuel type 4	Fuel type 5 (original fuel)
Preliminary core (Fig. 8)	k_{eff} = 1,03048 ± 0,00092 ρ = +3,79[βef]	k_{eff} = 1,04109 ± 0,00096 ρ = +5,06[βef]	k_{eff} = 1,03464 ± 0,00092 ρ = +4,29[βef]	k_{eff} = 1,02172 ± 0,00081 ρ = +2,73[βef]	k_{eff} = 1,05695 ±0,00099 ρ = +6,91[βef]

Tab. 4. Proposed parameters of IRT-2M fuel with 19.75% ^{235}U enrichment

Cladding [mm]	0,55
Enrichment [%]	19,75
Meat density [g/cm^3]	5,385
Partial uranium density [g/cm^3]	3,186
Amount of the ^{235}U in 3-tube fuel [g]	199,0
Amount of the ^{235}U in 4-tube fuel [g]	230,6

5. Proposal of Composition for IRT-2M Fuel with 19.75% ^{235}U Enrichment

On the basis of the evaluated results for the IRT-2M fuel geometrical setup designed for low-power research reactors with ^{235}U enrichment below 20% (the applicable value is 19.75% here), the fuel parameters stated in Tab. 4 appear to be the suitable ones. The parameters shown are similar to those stated by IRT-2M producer in the documentation delivered with the fuel.

6. Conclusions

The results indicate that the proposed composition of the fuel complies with both the task setting and with neutron-physical requirements. The fuel can be expected to reliably work in light-water basin reactors with power output of up to about 100 or 200 kW. The spare reactivity of the fuel that is necessary for the fuel burn-up is easily compensable in the defined configuration without necessity to replace the fuel. A prerequisite for successful operation is that 20 fuel elements should be ensured, which will provide for variability of the active core configuration in line with the reactor operator's actual needs.
Another step is to discuss the results with the fuel supplier and to try to purchase this, or a similar, type of fuel for the VR-1 reactor.

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